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InP-based heterostructure design and growth for semiconductor nanomembrane optoelectronics on Si and on flexible substrates

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The focus of this project has been on the realization of ultracompact microcavity lasers directly integrated on silicon. Using a stamp-assisted transfer-printing technology, silicon membrane-reflector vertical-cavity surface-emitting lasers (MR-VCSELs) based on transferred InGaAsP multiple-quantum well structures and two single-layer Fano resonance photonic crystal membrane reflectors on silicon substrate have been realized. Optically pumped MR-VCSELs are demonstrated as well as electrically pumped light-emitters on silicon.

The demonstration of ultra-compact and DBR-free VCSELs directly incorporated on a silicon substrate using a viable multi-membrane transfer-printing process can be expected to be of major interest for a range of applications in optoelectronics, photonic devices and photonics-electronics integration. The present results obtained here constitute an important first step towards the ultimate realization of low-threshold, energy-energy efficient MR-VCSELs on silicon or other substrates.

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Summary

The focus of this project has been on the realization of ultracompact microcavity lasers directly integrated on silicon. Using a stamp-assisted transfer-printing technology, silicon membrane-reflector vertical-cavity surface-emitting lasers (MR-VCSELs) based on transferred InGaAsP multiple-quantum well structures and two single-layer Fano resonance photonic crystal membrane reflectors on silicon substrate have been realized. Optically pumped MR-VCSELs are demonstrated as well as electrically pumped light-emitters on silicon. Work on electrically pumped MR-VCSELs is still in progress.

1. Introduction

The direct integration of compact and power-efficient laser sources on a silicon platform is highly requested for the full-scale realization of a silicon-based integrated electronics-photonics technology. This presently represents a mainstream worldwide research field with a variety of competing technologies being put forward, including silicon-based light sources as well as the heterogeneous integration of silicon with compound semiconductor materials using heteroepiatxial growth or various kind of wafer bonding; see Ref. 1 for a recent review. While promising results thereby have been reported, there are still materials and processing issues that needs to be resolved before any large-scale implementations can take place. In short, silicon-based light sources suffers from poor efficiency, heteroepitaxy results in a high-density of strain-driven defects requiring the application of thick buffer layers and/or complex growth schemes, and direct wafer bonding or fusion have very stringent requirements on the surface preparation.

In the present project, we make use of a low-temperature membrane transfer-printing and stacking fabrication process[2] to build ultra-compact silicon membrane reflector vertical-cavity surface-emitting lasers (MR-VCSELs) directly on the silicon wafer. This approach has several advantages. For instance, it allows the fabrication of lasers on silicon or any other low-cost or low-temperature substrate without the need for wafer bonding, it corresponds to an efficient use of the III/V materials in the laser fabrication process, and it has the ability to form single- or multi-wavelength laser arrays in an arbitrarily distribution on the surface[2]. Of specific importance is also that the application of very thin membrane reflectors allows the fabrication of area- and power-efficient VCSELs that also correspond to more straightforward fabrication and testing as compared to the edge-emitting lasers so far commonly used in the efforts for building on-silicon lasers.

The initial part of the project was focused on optically pumped MR-VCSELs with the target to demonstrate the concept as such and to optimize the structure. Single- and multi-wavelength lasing was observed over a large temperature interval (10-300 K)[3] and it was demonstrated how the pumping threshold could be reduced from an improved cavity design and thermally engineered layers for optimized heat dissipation[4]. In a second part of the project, double intracavity contacts for electrically injected devices were implemented. Cavity-enhanced light emission at the design wavelength (around 1.55 μm) was thereby obtained at room temperature. However, a pre-mature thermal roll-over in the emission power was observed with increasing injection current and lasing was not achieved[5]. Further optimization of the active region and the overall device design is presently on-going for the realization of electrically pumped MR-VCSELs.

2. Methods, Assumptions and Procedures

Figure 1 a) illustrates the basic configuration of the MR-VCSELs. In contrast to an ordinary VCSEL structure which uses multilayer distributed Bragg reflectors (DBR) of significant thickness, the MR-VCSEL basically consist of a five-layer structure as indicated in Fig. 1. The resulting thickness of the MR-VCSEL is only around 2 µm, to be compared with a thickness of maybe 20 µm for an ordinary InP-based VCSEL at this wavelength. Such compact laser structures are highly desirable for silicon-photonic applications, but the ultra-small cavity is also expected to lead to improved VCSEL-performance in terms of power efficiency and modulation bandwidth[6].

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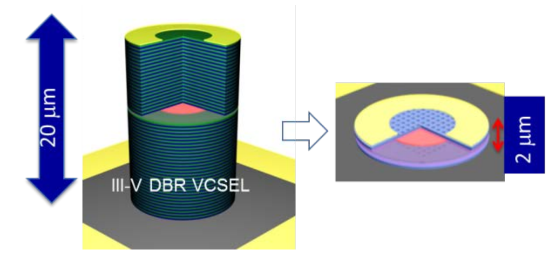

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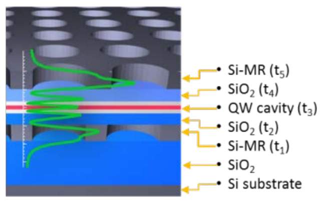

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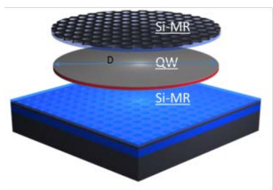

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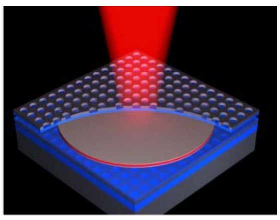

Figure 1. a) Size comparison between a VCSEL with conventional semiconductor DBR structures and a MR-VCSEL with ultrathin membrane reflectors; **b)** Schematic view of the VCSEL cavity with active gain region. The calculated standing wave electromagnetic field distribution is indicated; **c)** Illustration of the multilayer printing process for the formation of the MR-VCSEL; and **d)** the complete structure under lasing.

The InP-based cavity structure, with layer structure as shown in Fig. 2, is grown by metal-organic vapor-phase epitaxy (MOVPE) and consists of an InGaAsP multiple-quantum-well (MQW) structure, InP cladding layers and highly doped InGaAs contact layers. The MQW structure consists of eight compressively strained InGaAsP quantum wells embedded in nine tensile strained InGaAsP or InAlGaAs barriers, resulting in full strain compensation (zero net strain). Samples with InAlGaAs barriers are included due to the higher conduction band offset to the InGaAsP wells and thereby an expected improvement in high-temperature operation[7]. However, due to the Al content, these structures are somewhat more challenging in the fabrication process and all experiments have so far been performed using InGaAsP barriers.

Layer	Description	Material	Thickness (nm)	Dopant	Doping (cm^{-3})	Optical Index	Optical Thickness
23	Contact layer	InP	30	Zn	5e18	3.172	0.0614
22	Cladding layer	InP	50	Zn	2e18	3.172	0.1023
21	Spacer layer (Q1.2)	$In_{0.78}Ga_{0.22}As_{0.479}P_{0.521}$	91.1	Undoped (UID)		3.317	0.19495
20	Barrier (0.9% ts)	$In_{0.485}Ga_{0.515}As_{0.83}P_{0.17}$	7	Undoped (UID)		3.4	0.0154
5…19	Quantum wells (1% cs) (x8)	$In_{0.76}Ga_{0.24}As_{0.83}P_{0.17}$	8	Undoped (UID)		3.5	0.1445
4…18	Barrier (0.9% ts) (x8)	$In_{0.485}Ga_{0.515}As_{0.83}P_{0.17}$	7	Undoped (UID)		3.4	0.1228
3	Spacer layer (Q1.2)	$In_{0.78}Ga_{0.22}As_{0.479}P_{0.521}$	91.1	Undoped (UID)		3.317	0.19495
2	Cladding layer	InP	50	Si	2e18	3.172	0.1023
1	Contact layer	InP	30	Si	5e18	3.172	0.0614
	Sacrificial layer	InGaAs	500	Si	5e18		
InP Substrate (n+)							

Figure 2. Layer structure for the MOVPE grown optical cavity structure, including the MQW active gain and contact regions. In some samples the InGaAsP barrier layers were replaced by InAlGaAs based ones with similar amount of tensile strain to compensate the compressively strained QWs.

The MR-VCSEL fabrication process is illustrated in Fig. 3. The photonic crystal Si reflectors were fabricated using e-beam lithography and reactive ion etching on SOI substrates (340 nm silicon and 2 µm buried oxide). A low-index SiO_2 layer was deposited with plasma-enhanced chemical vapor deposition (PECVD) on top of the patterned silicon layer to form the bottom MR[8]. The InP-based active region was released from the InP substrate using a selective wet-etching process and then transferred onto the lower silicon MR using a semiconductor nanomembrane transfer printing and stacking process, employing a polydimethylsiloxane (PMDS) stamp[2]. In a subsequent step, the upper silicon MR was transferred onto the top of the transferred crystalline InP layer. While the top and bottom silicon MRs are in the form of single pieces, the InP layer was transferred in the form of separated disks. Figure 4 shows scanning electron microscopy (SEM) images of fabricated MR-VCSELs for optical pumping. To realize electrically pumped devices, intracavity ring contacts were formed on double-step p- and n-mesas before transfer onto the lower silicon-MR.

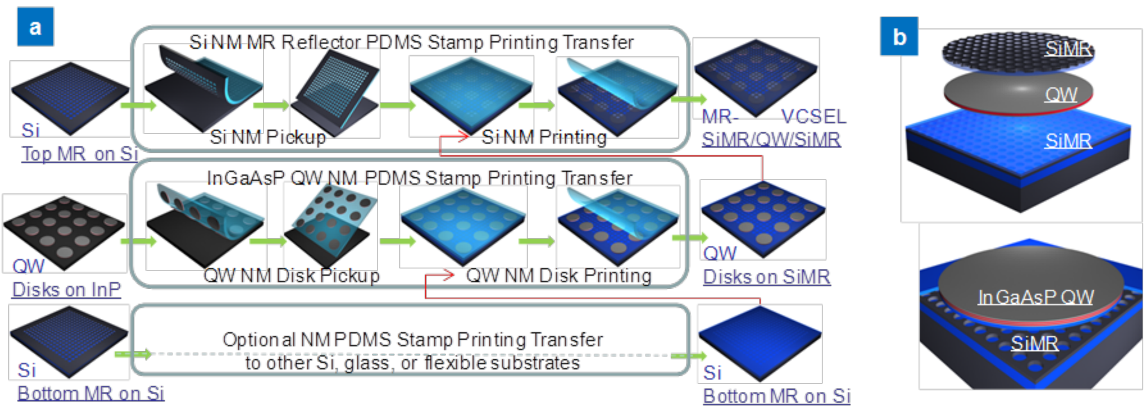

Figure 3. a) Schematic illustration of the multilayer transfer printing process for the fabrication of MR-VCSELs; **b)** Illustration of the complete device structure.

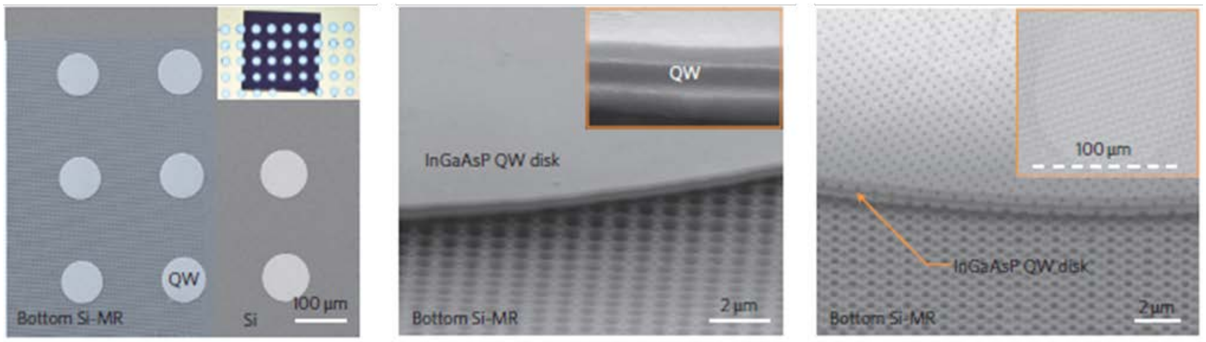

Figure 4. Scanning electron microscopy images of fabricated MR-VCSEL structures for optical pumping. **(left)** InP active layer/cavity disks after the transfer onto the bottom silicon MR. (inset) Optical micrograph showing the bottom silicon MR as a dark region; **(center)** Magnified view of the InP-based disk after deposition onto the lower silicon MR. (inset) Zoom-in on the InGaAsP/InGaAsP QW MQW region; **(right)** The completed MR-VCSEL.

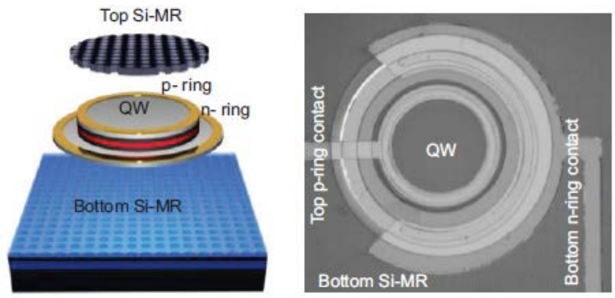

Figure 5. (left) Schematic illustration of electrically pumped MR-VCSEL structure; **(right)** SEM micrograph of fabricated MR-VCSEL before deposition onto the top silicon MR.

3. Results and Discussion

3.1 Optically pumped devices

MR-VCSELs were fabricated according to two different designs, optimized for operation at low temperature and room-temperature, respectively. The active layer and material gain is thereby kept constant but the cavity resonance is set at a shorter wavelength (1450 nm) in the former case and at a longer wavelength (1550 nm) in case of the room-temperature design. Lasing was obtained in both these cases; see Fig. 6 for a summary of the device characteristics.

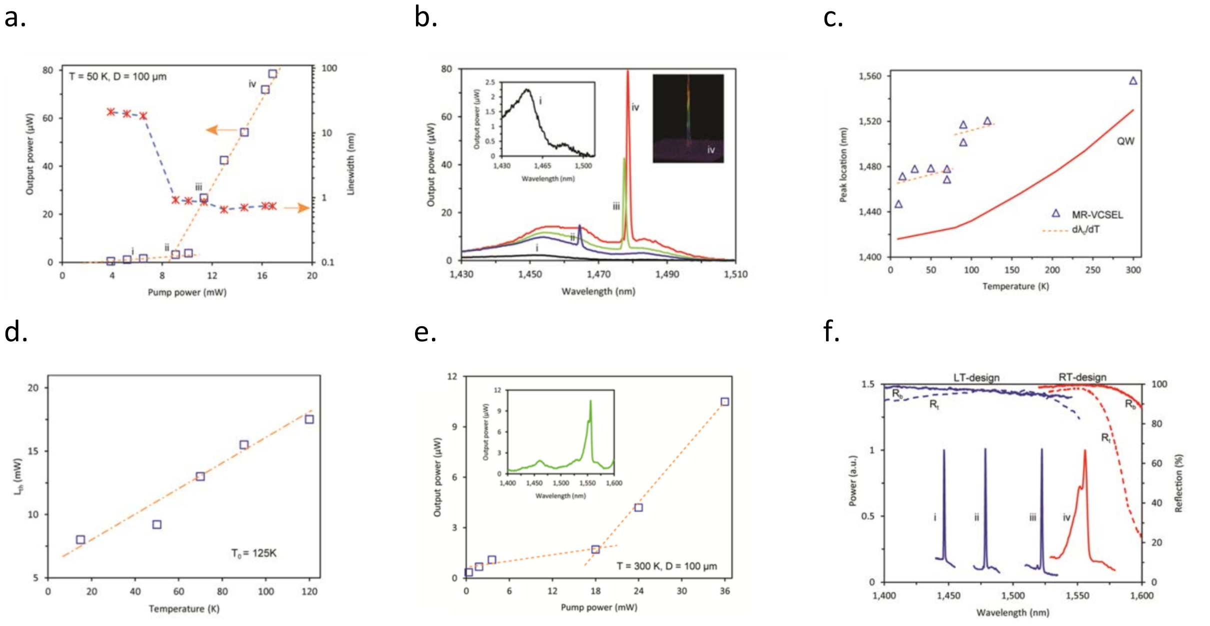

Figure 6. Operational characteristics of optically pumped MR-VCSELs: **a)** Lasing power and optical linewidth as function of pump power (low-T design); **b)** Optical spectra under different pumping conditions; i and ii below and iii and iv above lasing threshold (low-T design); **c)** Temperature-dependent emission wavelength and MQW gain peak. A mode hopping occurs around 80 K. (low-T design); **d)** Temperature-dependent threshold power yielding a characteristic temperature of 125 K (low-T design); **e)** Optical output power versus pump power measured at room temperature. (inset) Corresponding optical spectrum (room-temperature design); **f)** Optical spectra measured at different temperatures: i) 10 K; ii) 50 K; iii) 120 K; iv) 300 K. The spectral reflectance of the bottom (r_b) and top (r_t) MRs is also indicated. (Blue: Low-T design; Red: room-temperature design).

The thermal performance of the first generation MR-VCSELs was mainly limited by the use of buffer layers with modest thermal conductance and a short-wavelength (532 nm) pump source that effectively heats all layers in the cavity. In Fig. 7, we show how the threshold power can be significantly reduced from by using a long-wavelength pump source of 980 nm. Further improvements are expected from an optimized cavity design and the incorporation of highly thermal conductive buffer layers.

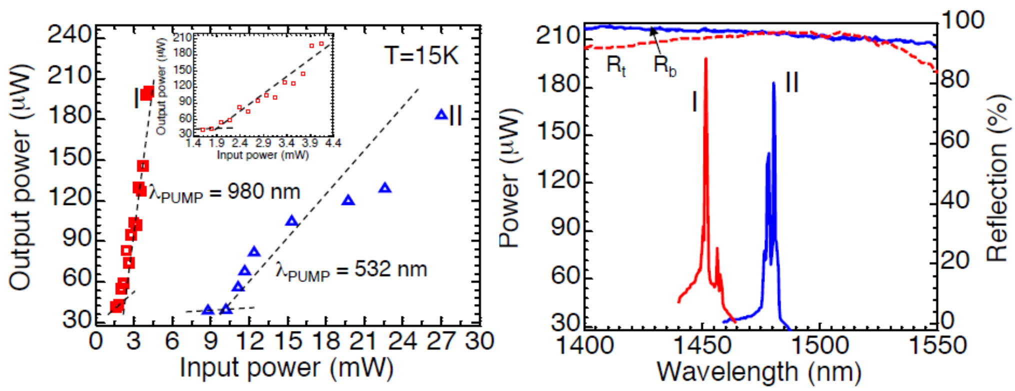

Figure 7. Comparison of the low-temperature MR-VCSEL performance under different pumping conditions (980 or 532 nm pump wavelength): **a)** Laser output power versus input pump power; (inset) zoom-in on the 532 nm characteristics; **b)** Optical spectra corresponding to the two different pump wavelength (Red: 980 nm; Blue: 532 nm). Also shown is the spectral reflectance from the bottom (r_b) and top (r_t) MRs.

3.2 Electrically pumped devices

MR-VCSELs for electrical injection were processed according to the design depicted in Fig. 5 above. The operational characteristics of these devices are shown in Fig. 8. By virtue of the double intracavity contacting scheme an excellent current-voltage characteristic with a very low turn-on voltage is noted (Fig. 8 a). Figure 8 b shows the measured optical spectra before (Half Cavity) and after (Full Cavity) the transfer of the top silicon MR. Drastically reduced linewidth in combination with enhanced peak intensity at the same clearly indicates cavity enhanced emission. This conclusion is further supported by the observation of longer-wavelength peaks in the off-normal directions (Fig. 8 c). However, the output power saturated with increasing bias current due to Joule heating. Further cavity design and process optimization is presently ongoing for the realization of electrically pumped MR-VCSELs.

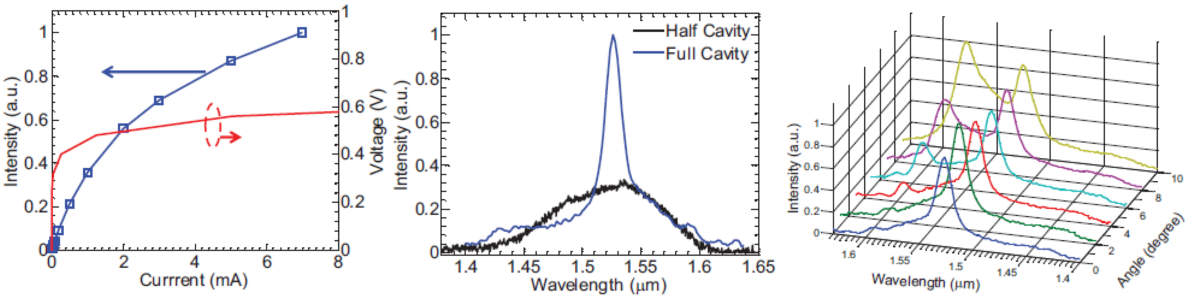

Figure 8. Room-temperature characteristics of electrically pumped MR-VCSEL: **a)** Light-versus-current and voltage-versus current characteristics; **b)** Optical spectra as measured on the half-cavity before transfer of the top silicon MR and on the full structure; **c)** Angle-dependent optical spectra for a bias current of 1 mA.

4. Conclusions

The demonstration of ultra-compact and DBR-free VCSELs directly incorporated on a silicon substrate using a viable multi-membrane transfer-printing process can be expected to be of major interest for a range of applications in optoelectronics, photonic devices and photonics-electronics integration. The present results obtained here constitute an important first step towards the ultimate realization of low-threshold, energy-energy efficient MR-VCSELs on silicon or other substrates.

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